The impact of maize stand density on herbicide efficiency

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ABSTRACT

The impact of maize stand density (4, 8 and 12 plants per m^2) on herbicide efficiency (in %) and cob yield loss (in %) was studied in four field trials. The mixture of soil-applied herbicides (HS) isoxaflutole and S-metolachlor and the mixture of foliar-applied herbicides (HF) dicamba and rimsulfuron was applied in two dosages (100 and 75% of dose recommended by manufacturers). The 100% dose of HS was (75 g isoxaflutole + 960 ml S-metolachlor) per ha and 100% dose of HF was (12.5 g rimsulfuron + 240 ml dicamba) per ha. In all four trials, the studied factors (stand density, herbicide type and dose) had significant impact on herbicide efficiency and on maize cob yield loss. The herbicide efficiency decreased significantly, when herbicides were applied to maize of lower stand density and the maize yield losses increased. When weed population was composed predominantly of annual seed weeds higher efficiency was obtained by HS herbicides, conversely, when the weed population was composed predominantly of perennial weeds the HF herbicides provided better control. The reduction of herbicide dose always caused the significant reduction in herbicide efficiency and increase in maize yield loss.

Keywords: maize; stand density; yield loss; herbicide efficiency; isoxaflutole; S-metolachlor; dicamba; rimsulfuron

An enormous increase in public concern for the protection of the environment and increased awareness of pesticide residues in food and water, have necessitated a renewed appraisal of current crop production systems for all crops. In Slovenia maize is the most important field crop and the most problematic from an ecological point of view (herbicide residues in ground water). We are intensively studying the possibilities to reduce the herbicide use in maize production. In literature, many possibilities for reaching that goal are presented.

The main possibilities from them are: use of lowered doses of herbicides (Mulder and Doll 1993, Rola et al. 1999), use of banded instead of broadcast application (Hamil and Zhang 1995, Heydel et al. 1999), banded application combined with between-row mowing (Donald et al. 2001), intensification of mechanical weed control methods combined with reduced doses (Schans and Weide 1999, 2000), use of technology of living or dead mulch and cover crops (Ammon et al. 1995, Barberi 1997), weed flaming, use of mycoherbicides, patch spraying, changed seeding systems and mixed crops (Froud-Williams 1995, Ammon 1997).

None of them are completely suitable for ecological and economical situations in all countries around the world. The use of lowered herbicide doses is the simplest way for reducing herbicide use without changing the production technology significantly. Slovenian farmers often search for information on methods for weed suppression with lowered herbicide doses. In literature, we can find interesting information on possibilities of drastic reduction of herbicide doses without causing the significant increase in maize yield losses. Most reports present cognitions that doses of herbicide can be lowered by 15 to 30% without a significant impact on yield loss in situations with moderate weed pressure and when at least one mechanical weed control treatment in season is carried out (Rola et al. 1999, Schans and Weide 2000). Some authors have also established that greater reductions of herbicide doses (50–70%) can provide satisfactory weed control and good economic return in suitable conditions (Forcella 1995, Schans and Weide 2000). A few experiments revealed possibilities of 80% (Alm et al. 2000), or even 90% (Weide et al. 1995) of herbicide dose reduction without risk for significant increase in yield loses.

According to our experiences in Slovenian conditions we are sceptical about some results that report 50 to 80% herbicide dose reduction without a significant impact on yield losses. In our study, we wanted to test the possibility of reduction of herbicide dose by 25% in the case of two herbicide mixtures, which are often used by Slovenian farmers. By taking into consideration our ecological and pedological conditions in fields, which are very suitable for weed development (a lot of rain, rich and intensively fertilized soils) we assume, that greater reductions are too risky in terms of yield loss. We also wanted to demonstrate how the competitive ability of maize, which is directly connected to stand density and to the speed of crop development, is important when we decide to control weeds with lowered herbicide doses.

MATERIAL AND METHODS

To analyse the impact of maize stand density on herbicide efficiency rate, four field trials were carried out in the maize fields in the northwestern part of Slovenia. The locations, types of soils and growing technology are given in Table 1. We selected four locations with different types of soil and different weed populations. Despite

Table 1. Soil types and basic technology practice on trial locations

Trial location	Soil type clay (%)	Organic matter (%)	pH	Sowing date	Date of yield assessment
Slape 1999	alluvial sandy loam (8)	3.8	6.9	April 25	October 3
Hoce 2000	gleyed brown soil (22)	2.4	6.4	April 28	September 25
Hoce 2001	distric brown soil (12)	1.8	6.1	April 30	September 26
Gaj 2001	pseudogleyed clay loam (34)	2.1	5.8	April 26	October 1

differences in soil types, the fertility and supply of main nutrients (N, P, K) was high and very similar in all selected locations. In previous experiments in the selected fields, we obtained information on weed seed banks (the number of seeds per m^2 in a 25cm soil layer) and the rates of emergence.

The species compositions of studied weed populations are presented in Table 2. The maize was grown intensively according to the local manner. In all four trials, plots were fertilised with 200 kg N, 160 kg K_2O and 90 kg P_2O_5 per hectare yearly.

In each of four trials, factorial randomised block design was used with four replications of treatments. Three factors and their interaction were investigated, the first being the maize stand density (MD = number of maize plants per m^2), the second was the herbicide type (HS = soil applied herbicide versus HF = foliar applied herbicide), and the third was herbicide dose (100 and 75% of recommended dose).

The levels of factor maize stand density were: MD12 = 12 maize plants per m^2, MD8 = 8, MD4 = 4 and MD0 = 0 maize plants per m^2 (control plot). Two mixtures of herbicides were studied. HS was a mixture of two soil-applied herbicide preparations (Merlin + Dual gold) and the HF was a mixture of two foliar-applied herbicide preparations (Tarot + Banvel). For detailed information about herbicides and application, see Table 3.

Both types of herbicides were applied in two dosages. The first was a 100% dose as recommended by manufacturers (HS100 and HF100) and the second was a 75% of recommended dose (HS75 and HF75). In each block, there were also plots of maize grown without competition with weeds and plots that were not treated with herbicides. Those plots were control plots for calculation of maize cob yield losses and for calculation of herbicide efficiency. Weed-free plots were weeded by hand several times throughout the season.

The plots of 4.2 × 4 m were formed in the fields on the day when the maize was sown by maize seeder. In all four experiments, the same maize hybrid was sown. That was hybride LG 23.10. produced by Sica L.G. Services (Limagrain), 63203 Riom. All the plots were seeded with 16 seeds per m^2 (70 × 9 cm). The between-row distance was 70 cm and within-row distance was 9 cm. When maize plants reached the two leaf stage, they were thinned by hand to achieve exact stand densities planned in the experiment (0, 4, 8, 12 plants per m^2).

The soil-applied and foliar-applied herbicides were applied by an air-pressured knapsack sprayer BASF-Gloria using Polyjet flat-fan 02-401/51 nozzle, delivering 300 l/ha of spray volume. During all the experiments, the soil and weather conditions were favourable for herbicide application and activity. The soil herbicides were applied two to four days after maize was sown and the foliar herbicides were applied when maize reached the 4 to 6 leaf stage and weeds reached the 3 to 5 leaf stage. One inter-row cultivation was carried out in the growing season, so there was a mechanical disturbance of weed growth in all plots. The cultivation with a goose-feet inter-row cultivator was carried out when maize plants reached a height of approximately 0.5 m (cultivation before canopy closing of maize stand in the last week of May).

Table 2. Species composition of weed population on untreated control plots (average values)

Trial location	Portion (%) of weight of each weed species on total weight																	TW
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Slape 1999	–	–	12	–	22	4	5	2	3	17	5	12	7	2	–	1	8	1.3–1.7
Hoce 2000	5	7	15	8	10	3	2	3	–	6	6	3	20	1	2	1	8	2.1–3.1
Hoce 2001	5	3	12	8	8	–	14	10	2	8	13	–	6	3	4	1	4	1.9–2.7
Gaj 2001	3	–	10	5	9	–	5	5	3	13	14	3	19	3	4	–	5	1.8–2.3

TW = total fresh biomass kg/m^2 of all weeds

1 – *Abutilon theophrasti*, 2 – *Ambrosia artemisiifolia*, 3 – *Amaranthus* sp., 4 – *Bidens tripartitus*, 5 – *Chenopodium album*, 6 – *Chenopodium polyspermum*, 7 – *Cirsium arvense*, 8 – *Convolvulus arvensis*, 9 – *Digitaria sanguinalis*, 10 – *Echinochloa cruss-galli*, 11 – *Elymus repens*, 12 – *Galinsoga* sp., 13 – *Polygonum* sp., 14 – *Setaria* sp., 15 – *Solanum nigrum*, 16 – *Stellaria media*, 17 – other weed species, 18 – all weeds together (100%)

Table 3. Doses and periods of herbicide treatments

Trial location	Preemergence treatment (HS)	Postemergenece treatment (HF)	Weed seeds bank (No. of seeds per m^2 in 25 cm soil layer)	Weed density (No. of emerged weeds per m^2 at application of HF)
Slape 1999	April 28	May 18	25 000–40 000	80–120
Hoce 2000	May 3	May 27	70 000–120 000	500–800
Hoce 2001	May 4	May 29	50 000–80 000	300–500
Gaj 2001	April 28	May 23	40 000–60 000	200–280

HS100 = (100 g Merlin + 1 l Dual gold)/ha = (75 g isoxaflutole + 960 ml S-metolachlor)/ha
HS75 = (75 g Merlin + 0.75 l Dual gold)/ha = (57 g isoxaflutole + 720 ml S-metolachlor)/ha
HF100 = (50 g Tarot + 0.6 l Banvel)/ha = (12.5 g rimsulfuron + 240 ml dicamba)/ha
HF75 = (75 g Merlin + 0.45 l Banvel)/ha = (9.4 g rimsulforon + 180 ml dicamba)/ha
Merlin = (75% isoxaflutole) – Aventis CS, Dual gold 960 EC = (96% S-metolachlor) – Syngenta
Tarot 25 WG = (25% rimsulfuron) – Du Pont, Banvel 480 S = (48% dicamba) – Syngenta

At the end of the vegetation period in the middle of all the plots, 2.1 × 2 m areas were marked by using string. All the weeds from the marked area were reaped by hand and gathered to be weighed. The total weight of collected weeds (aboveground plant parts) was estimated and then the average values of kg fresh weight of weeds per m^2 were calculated. In addition, maize cobs from plants within the marked area were gathered and the yield of fresh cobs (kg/m^2) was established.

The herbicide efficiency (HE %) was calculated according to the modified Abbot formula, which is usually used for insecticide and fungicide evaluations (Bleiholder 1989):

HE (%) = [(weight of weeds in untreated plot – weight of weeds in treated plot)/(weight of weeds in untreated plot)] × 100

For efficiency calculations we always compared weights of weeds between treated and untreated plots with the same maize stand density (4 treated/4 untreated, 8 treated/8 untreated…). Maize cob yield losses were also calculated according to comparisons between treated plots and weed free plots of the same maize stand density (4 treated/4 weed free…).

The statistical analysis was performed using SPSS 10.0 for Windows software. Data were subjected to analysis of variance with treatment means compared using Tukey's tests at ($\alpha = 0.05$) probability level. Data on maize yield losses (%) and on herbicide efficiency (%) were arcsine, square-root transformed before the analysis of variance was performed. Data presented in tables and graphs are not transformed.

RESULTS AND DISCUSSION

In all four trails, the studied factors (stand density, herbicide type, herbicide dose) had a significant impact on herbicide efficiency and on maize cob yield loss (Table 4 – main effects). The most significant was the impact of maize stand density. In each trial, some interactions between main factors were significant and some were not (Table 4 – interactions). The use of lowered dose (75%) of herbicide mixtures always caused the decrease of herbicide efficiency and the increase of maize cob yield loss. The rate of herbicide efficiency decrease and of maize cob yield loss increase was different in all four trial locations, depending mainly on differences in species composition of weed populations and weed emergence rates (weed pressure).

Table 4. Results of tests of factor and interaction significance in analysis of variance for full factorial design

	Trial location	Slape 1999		Hoce 2000		Hoce 2001		Gaj 2001	
	Source of variation	HE	YL	HE	YL	HE	YL	HE	YL
Main factors	MD – stand density (0, 4, 8, 12)	**	**	**	**	**	**	**	**
	HT – herbicide type (HF, HS)	**	**	**	**	**	**	**	**
	HD – herbicide dose (100%, 75%)	**	**	**	**	**	**	**	*
Interactions	MD × HT			*					
	MD × HD				**				*
	HT × HD		**	*	*	**	*	*	
	MD × HT × HD			*	*				*

HE = herbicide efficiency, YL = maize cob yield losses
*, ** significant impact of a factor or interaction on studied parameters according to the *F*-test at ($\alpha = 0.05$) or ($\alpha = 0.01$) probability level, respectively

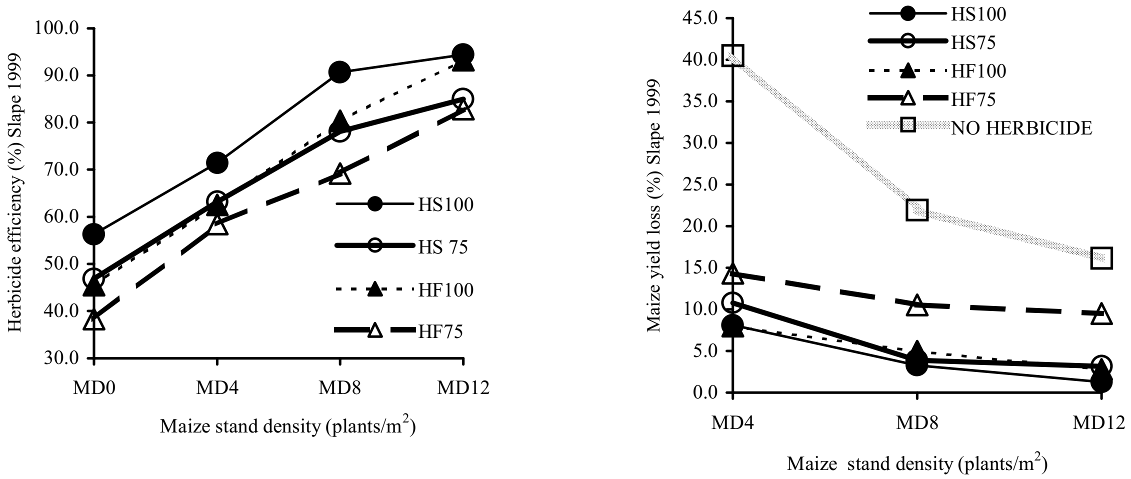

Figure 1. Herbicide efficiency and maize yield loss according to the maize stand density, herbicide type and herbicide dosage in trial Slape 1999; means marked with the same later do not differ significantly according to Tukey's tests at (α = 0.05) probability level

Slape 1999

In the trial at the Slape location, there was no interaction between main factors when we analysed herbicide efficiency, but in the case of cob yield loss there was a significant interaction between herbicide type and herbicide dose. The weed population was composed predominantly of a small number of annual seed weeds, which presented low weed pressure on the maize crop. Only 80–120 weeds emerged per m^2 (at HF application) and the average biomass of fresh weeds in untreated plots in the autumn amounted to 1.3–1.7 kg/m^2. Therefore, the yield loss was moderate in the herbicide treated and the untreated plots of all maize stand densities. In untreated plots of MD4 the loss amounted to 40.5%, in MD8 to 22% and in MD12 to 16.2%. The 25% reduction of herbicide dose caused a higher decrease of efficiency at HF than at HS herbicide mixture (Figure 1). The reduction of dose caused an average increase of yield loss from 4.2 to 6% at HS and from 5.3 to 11.5% at HF herbicide mixture. In field situations like at the Slape location the 15–20% dose reduction of similar herbicide mixtures could be advised to farmers without great risk of increase in yield loss, when at least one inter-row cultivation is planned.

Hoce 2000

At the Hoce location in the year 2000 we had to suppress a large weed population, which presented severe weed pressure to the maize crop. At the time of HF application, we determined 500–800 weed seedlings per m^2 and in the autumn the average biomass of fresh weeds amounted from 2.1 to 3.1 kg/m^2 (Table 2). The weed biomass was mainly composed of annual seed weeds (*Amaranthus* sp., *Chenopodium* sp. and *Polygonum* sp.). The yield losses were great in herbicide treated and untreated plots (Figure 2). The reduction of herbicide dose resulted in a great increase of yield loss for both herbicide mixtures and at all stand densities.

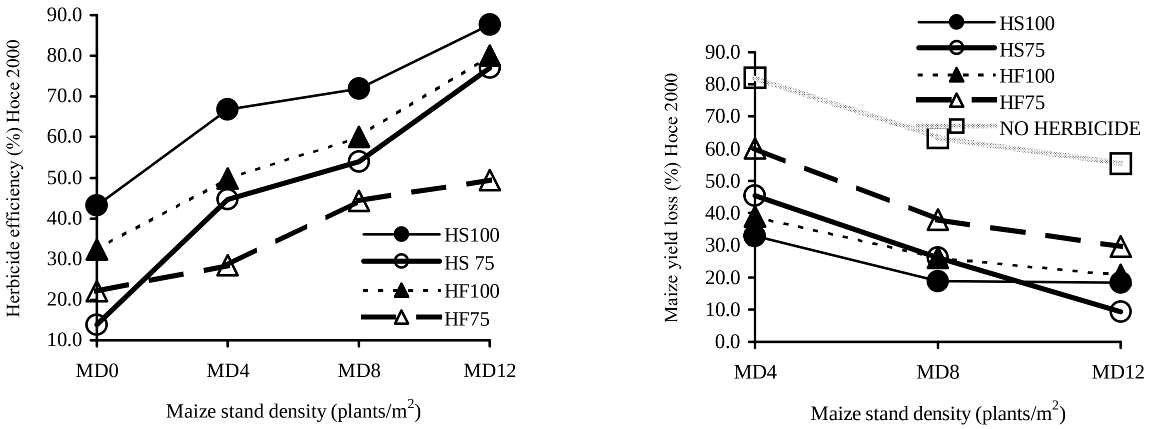

Figure 2. Herbicide efficiency and maize yield loss according to the maize stand density, herbicide type and herbicide dosage in trial Hoce 2000; means marked with the same later do not differ significantly according to Tukey's tests at (α = 0.05) probability level

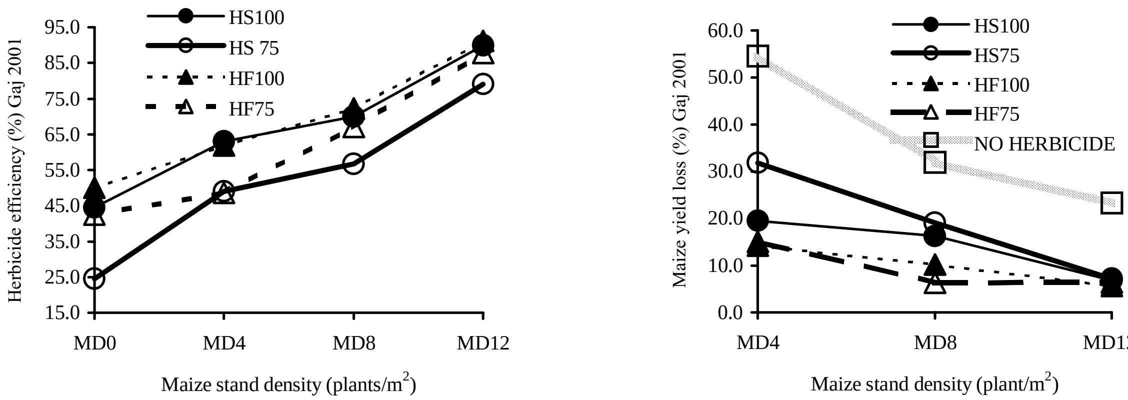

Figure 3. Herbicide efficiency and maize yield loss according to the maize stand density, herbicide type and herbicide dosage in trial Gaj 2001; means marked with the same later do not differ significantly according to Tukey's tests at (α = 0.05) probability level

In this trial, the importance of maize stand density was well demonstrated. In relation to stand density, the great differences between herbicide efficiency rates and yield loss rates could be observed in both types of herbicides. For example, the average efficiency of HF100% mixture at MD12 was 80%, but only 49.8% at MD4. When we have to suppress such a severe weed population, satisfactory control and economic return cannot be obtained by using lowered herbicide doses, although we plan to carry out two or three inter-row cultivations.

The results of this trial are also interesting for the interpretation of the relationship between the herbicide efficiency rate and maize yield loss. Usually it is expected that similar efficiency rates of herbicides provide similar success in weed control and result in similar yield loss prevention. Results of the Hoce 2000 trial demonstrate that the afore-mentioned statement is correct only when we compare the control of weed populations of similar species structure and density. The statement cannot be generalized. In the Hoce 2000 trial, the use of a 100% dose of HF resulted in 20.7% yield loss and the obtained herbicide efficiency was 80% (Figure 2). In the Slape 1999 trial 80.3% efficiency was obtained by using the same dose of the same herbicide mixture (HF100) and only 5% yield loss was determined (Figure 1). It is also possible that the yield losses at 70% efficiency of some herbicides in some fields would be smaller than in some other field where 95% herbicide efficiency would be reached. Therefore, it can be concluded that the same herbicide efficiency rates do not always result in the same success of weed control and prevention of yield loss.

Gaj 2001

The weed population in this trial was composed of both annual and perennial weeds. The weed pressure was moderate. On average, 200–280 weeds emerged per m^2 before application of HF mixture. In the autumn, the fresh biomass of weeds ranged between 1.8–2.3 kg/m^2. At the 100% dose and high maize stand density the difference in efficiency between HS and HF mixture was not great, but it increased significantly at low stand density and the 75% dose. The interaction between maize stand density and herbicide dose was significant. The success of control with 75% doses was greater with the HF herbicide mixture and, consequently, the losses of cob yield were smaller (Figure 3). That can be explained with species composition of weed population (Table 2). Perennial weeds (*Elymus repens* and *Convolvulus arvensis*) occupied a lot of growing space and it is well known that perennial weeds usually cannot be successfully controlled by using of soil-applied herbicides.

Hoce 2001

The perennial weeds (*Cirsuim arvense*, *Elimus repens* and *Convolvulus arvensis*) took a great share in total weed biomass (1.9–2.7 kg/m^2), consequently, like in the Gaj 2001 trial, the greater herbicide efficiency was obtained by the HF herbicide mixture and the decrease of efficiency by lowered 75% dose was smaller by the HF than the HS herbicides. The interaction between the herbicide type and herbicide dose was significant. The yield loss was great also with 100% doses of herbicides (Figure 4). In maize fields with such weed species composition and density, the use of lowered doses of herbicides could not be advised to farmers. Perhaps the reduction of herbicide dose would be possible by other herbicide mixtures or combinations of reduced rates of soil and foliar band-applied herbicides combined with two to three inter-row cultivations.

The results of trials show that the maize stand density has a significant impact on herbicide efficiency rate and, consequently, on cob yield loss. The differences between herbicide efficiency rates at different maize stand

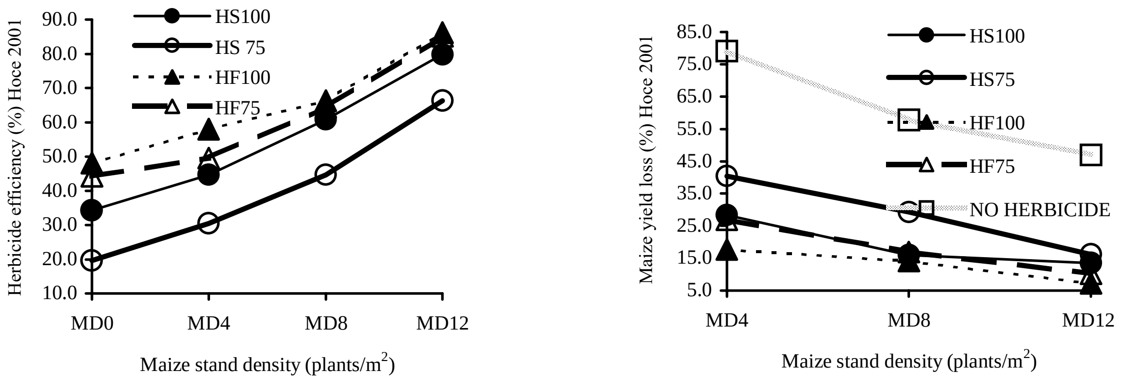

Figure 4. Herbicide efficiency and maize yield loss according to the maize stand density, herbicide type and herbicide dosage in trial Hoce 2001; means marked with the same later do not differ significantly according to Tukey's tests at ($\alpha = 0.05$) probability level

densities were big. Partly, statistically they are a result of the trial design. We also included 0 and 4 maize plants per m^2 density, which are not an option in real maize production, but they appear locally in real field stands, in case of unfavourable conditions (soil, weather, diseases, pests…) or when improper production practices are applied.

Maize competitive ability greatly depends on maize stand density and the speed of development. Because of this, farmers have to consider carefully if their maize crops have, or will have a good competitive ability. There are also great differences in competitive ability of maize hybrids (Ford and Pleasant 1994). In case that they are not able to assure the good competitive ability of maize, they should not practice weed control with use of lowered herbicide doses. By using sublethal doses, weeds are not controlled totally (incomplete weed kill). After a relatively short period, they can regrow if they are not additionally suppressed by maize.

The herbicide doses and efficiencies that are needed for successful suppression of weeds and prevention of yield loss differ significantly and depend a lot on the composition of weed population and specific local stand conditions. In dense maize stands with moderate weed pressure, many times we do not need to apply 100% doses of herbicides to hold the weed population below a threshold limit. It is difficult to determine exactly the rate to which the herbicide dose could be lowered in each specific situation in each specific field. Intensive research is carried out on modelling the interactions between weed density, crop density, reduced herbicide doses and yield loss. Best results were achieved in cereals (Kim et al. 2002), but for maize good practical models, still have not been developed.

In our environmental and production conditions, usually the good competitive ability of maize can be reached in stands where density exceeded 8 plants per m^2. According to the results of our trials we conclude that, in the case of broadcast application the reduction of herbicide doses by 10–25% could be advised to farmers, if weed population consists of less than 100 plants per m^2. Our findings are similar to the results of some researchers (Mulder and Doll 1993, Rola et al. 1999, Zhang et al. 2000) who also report that 15–30% reductions of herbicide doses could be advised to maize producers when they have to control moderate weed populations and maize has good competitive ability.

Usually it is concluded that further reduction of herbicide doses can be achieved by banded application and intensification of mechanical weeding. We agree with that, but it is well known that intensive mechanical weeding using machines also has many ecological disadvantages (greater consumption of petroleum, greater CO_2 emissions, greater soil compaction, bear soil effects, acceleration of nutrient leaching). In Slovenia, usually cost of one inter-row cultivation is approximately 50% of the cost for one broadcast herbicide application. That means that simple replacement of herbicide use with many mechanical cultivations is not the best solution, because we only replace some ecological benefits (less herbicides in soil and in water) with some ecological disadvantages, without having a noticeable economic benefit. Therefore, for reaching better ecological and economic effects in maize production, other distinct weed management strategies have to be considered and introduced in the near future.

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ABSTRAKT

Vliv hustoty setí kukuřice na účinnost herbicidů

Ve čtyřech polních pokusech jsme studovali vliv hustoty setí kukuřice (4, 8 a 12 rostlin na m^2) na účinnost herbicidů (v %) a na ztrátu výnosu kukuřičných palic (v %). Směs půdních herbicidů (HS) a směs listových herbicidů (HF) jsme aplikovali ve dvou dávkách (100% a 75% dávky doporučené výrobcem). 100% dávka HS představovala 75 g isoxaflutolu + 960 ml S-metolachloru na ha, 100% dávka HF představovala 12,5 g rimsulfuronu + 240 ml dicamby na ha. U všech čtyř pokusů měly pokusné faktory (hustota setí kukuřice, typ herbicidu a dávka herbicidu) statisticky významný vliv na účinnost herbicidů a na ztrátu hmotnosti výnosu palic. Ve všech případech byla u řidšího výsevu kukuřice účinnost herbicidů značně menší a ztráta výnosu vyšší. Pokud mezi plevely převládaly víceleté druhy, byla dosažena vyšší účinnost u HF herbicidů. V důsledku snížení dávky herbicidů o 25% se účinnost HS a HF herbicidů vždy znatelně snížila, a tím se značně zvýšila ztráta výnosu.

Klíčová slova: kukuřice; hustota setí; ztráta výnosu; účinnost herbicidů; isoxaflutol; S-metolachlor; dicamba; rimsulfuron

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